The LHCb RICH Upgrade

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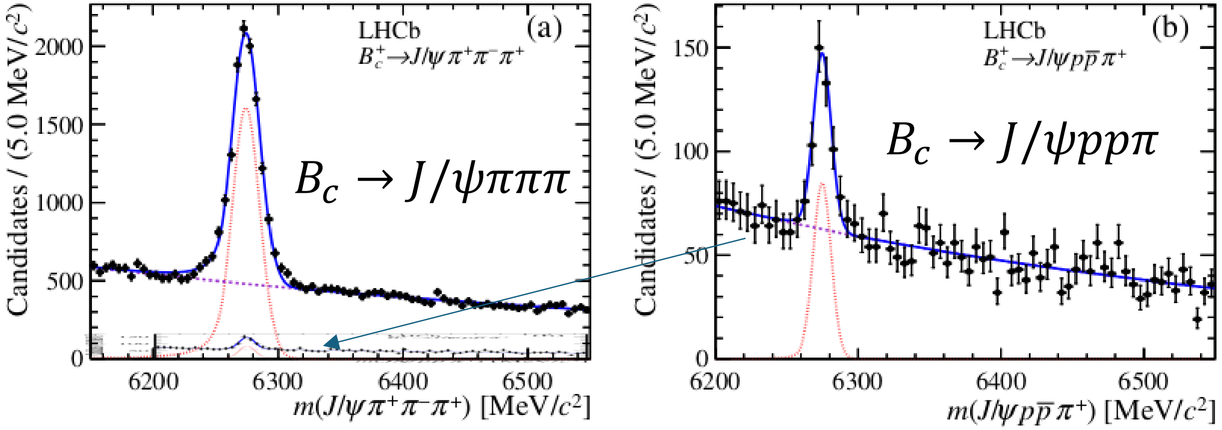
Outline

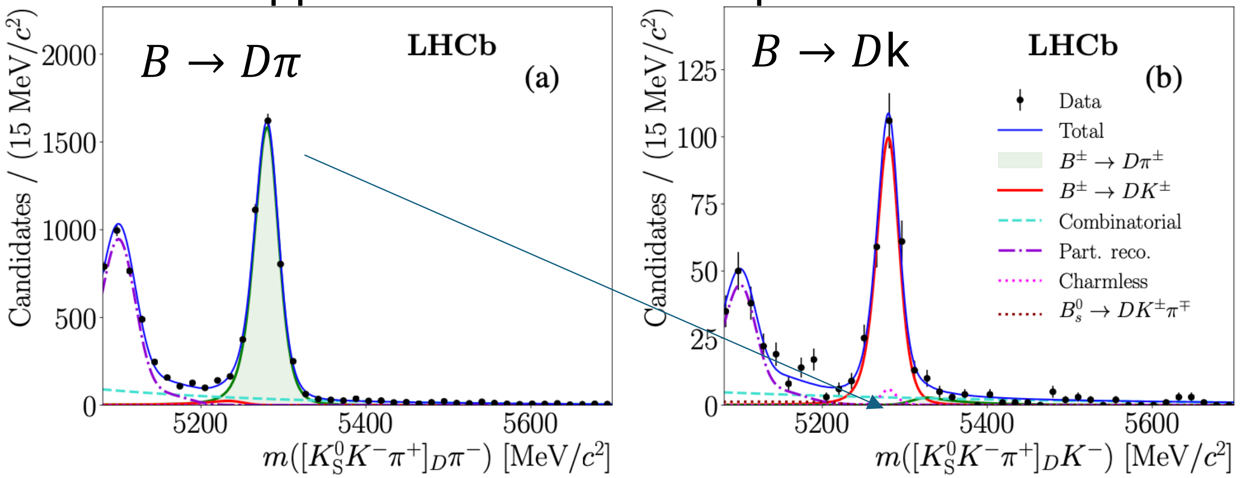
- Importance of Hadron Identification at LHCb
- The LHCb RICH Upgrade I in a nutshell
- Operations, optimization, calibration
- Performance with Run3 data

Hadron Identification at LHCb

Suppression of combinatorial background

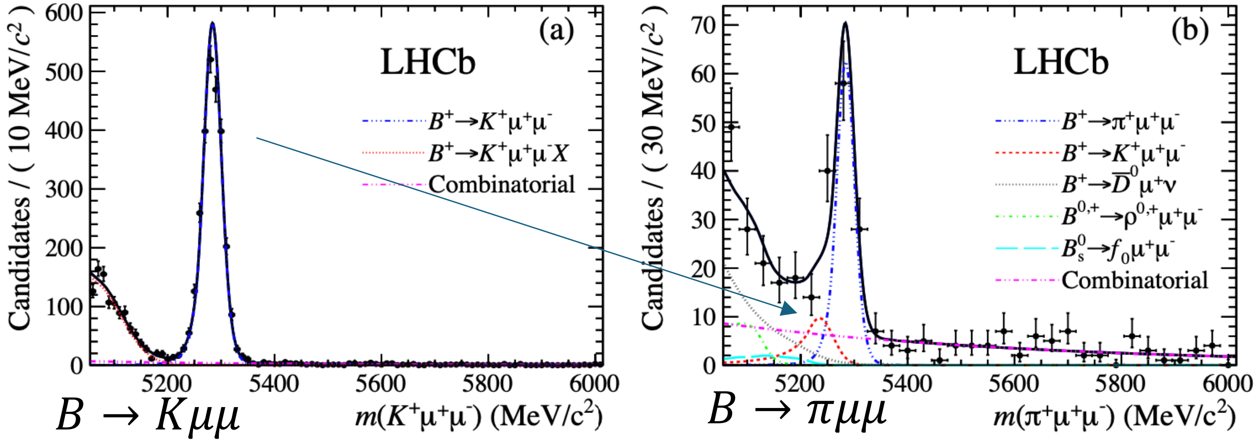


Suppression of dominant pion mode



- Charged Hadron identification for pions, kaons (and protons) in the range 2 – 100 GeV/c^2 (150 GeV/c^2)
- Combinatorial background suppression for all analyses
  - Events contain mostly pion tracks
- Separation of states otherwise with identical final state topology
  - Charmless decays from Cabibbo favorite modes
- B-Tagging

Suppression of dominant kaon mode

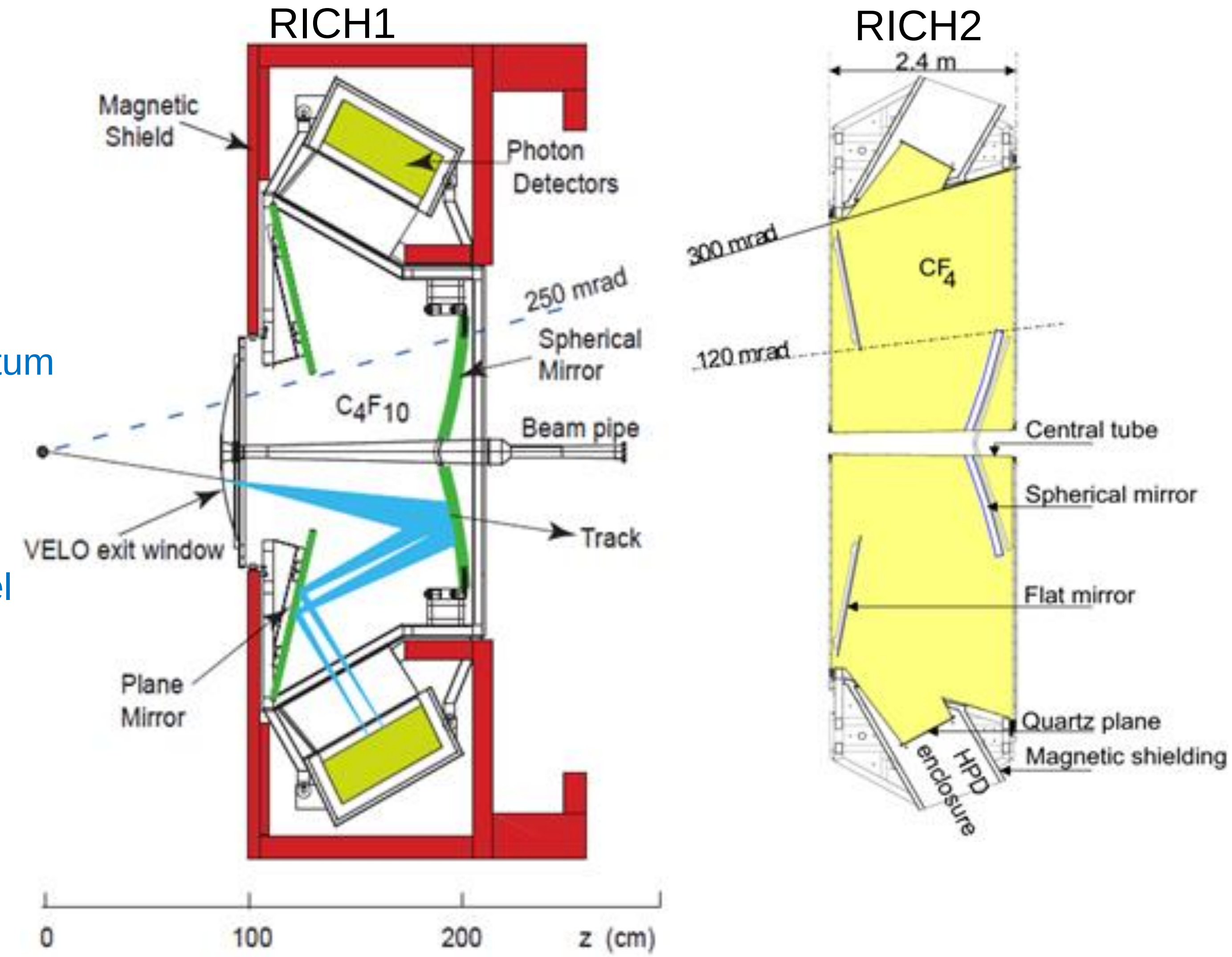


JINST 17 (2022) 07, P07013

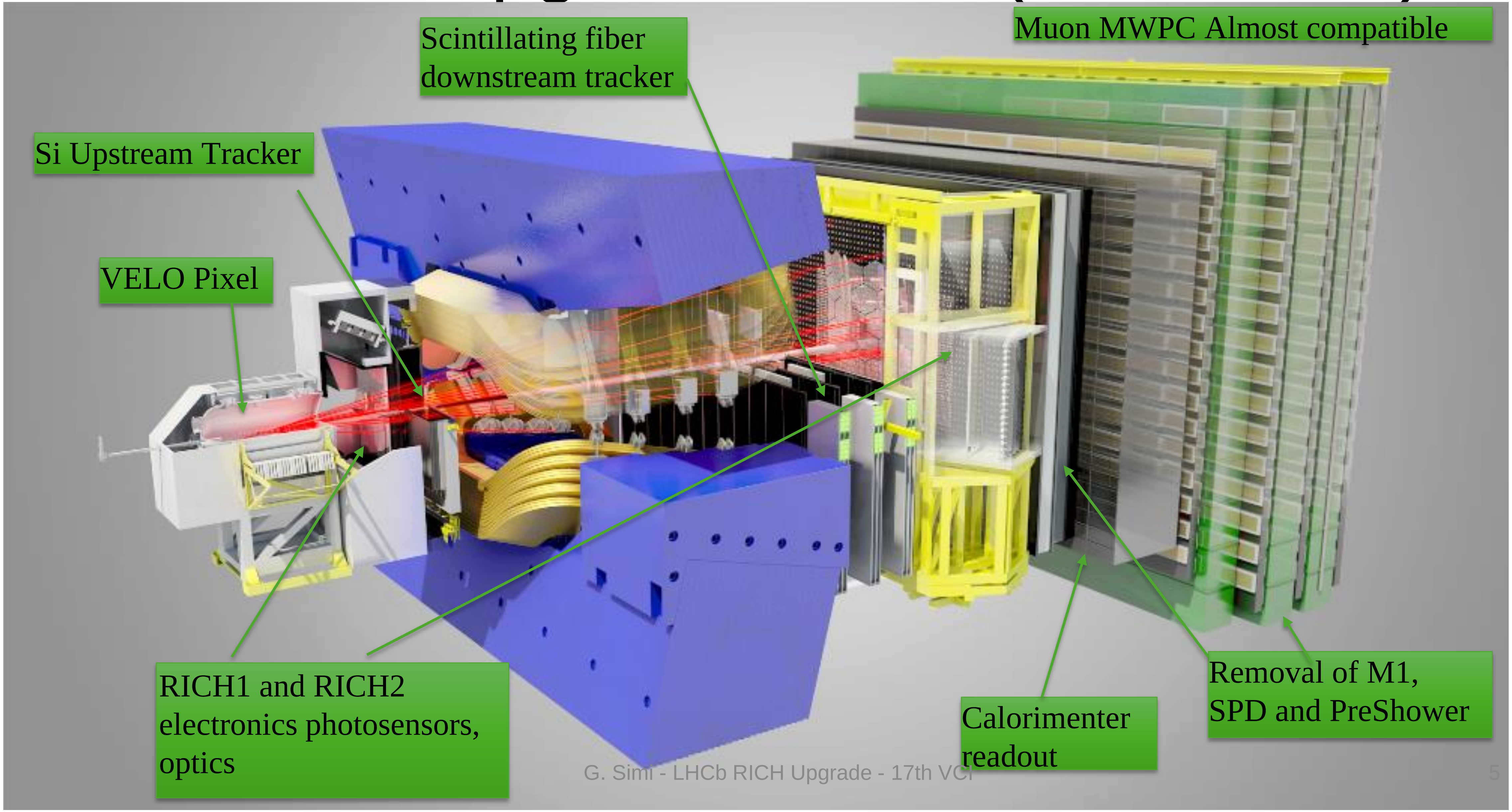
RICH performance basics

- Cherenkov angle resolution $\Delta\Theta_c = \frac{\sigma_c}{\sqrt{N_{ph}}} \oplus \sigma_{trk}$
- Intrinsic contributions to σ_c
  - σ_{cd} Chromatic dispersion
    - $\cos(\theta_c) = 1/\beta n(\lambda)$
    - Affected by radiator and detector quantum efficiency curve
  - σ_{ep} Emission point error
    - Affected by the spherical mirror tilt
  - σ_{pix} Photodetector granularity
    - Affected by mirror focal length and pixel size
- Contribution from tracking σ_{trk}
  - Track angle and momentum
- Charged hadron separation power

$$n_\sigma = \frac{|m_1^2 - m_2^2|}{2p^2 \Delta\Theta_c \tan(\Theta_c)}$$

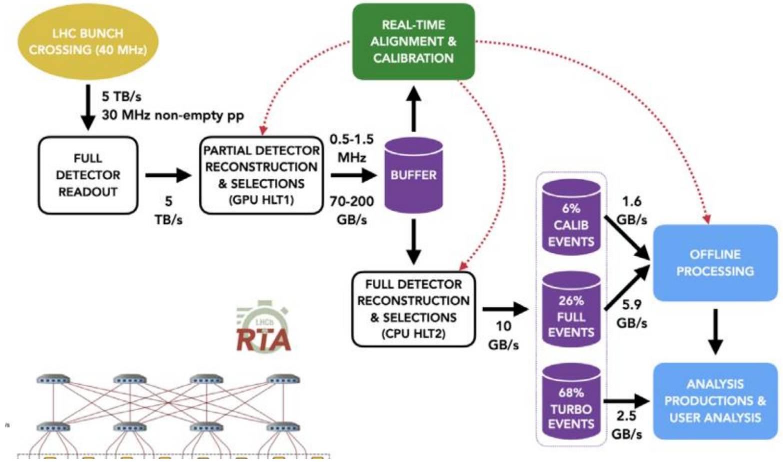


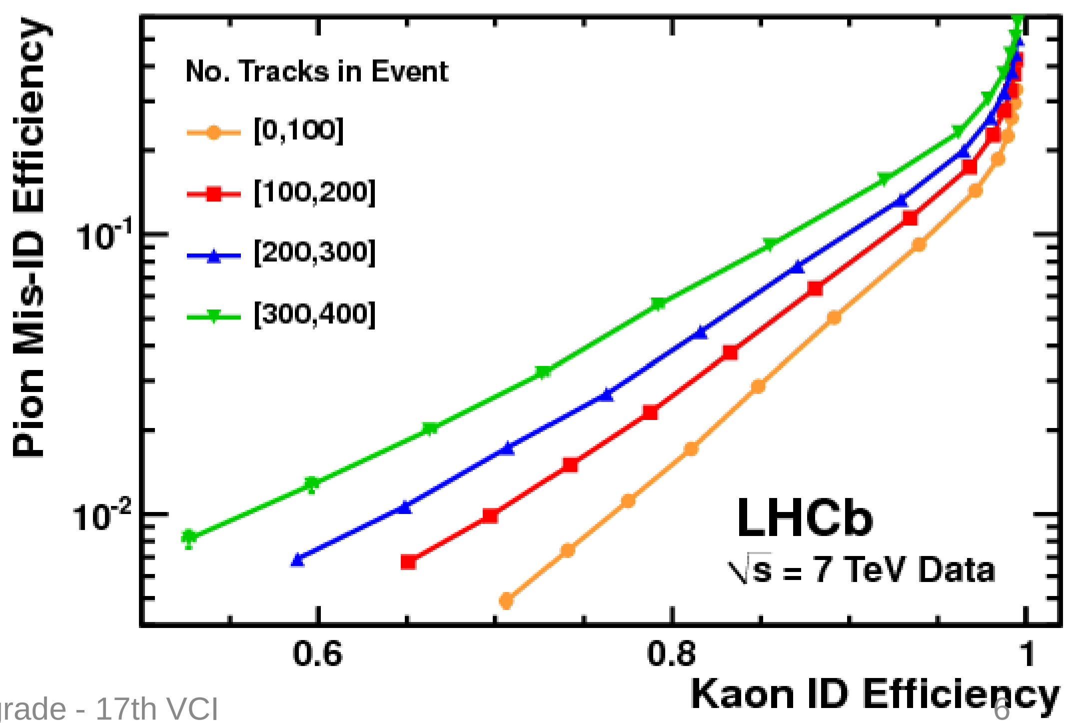
The LHCb Upgrade in LS2 (2020-2021)



RICH Upgrade: the challenge

- Removal of $L0$ Hardware trigger at 1MHz
  - Software trigger at 40MHz
  - → New electronics
- Instantaneous luminosity increase x 5
  - $4 \times 10^{32} cm^{-2} s^{-1} \rightarrow 2 \times 10^{33} cm^{-2} s^{-1}$
  - → Increased pileup
  - → Increased number of primary vertices N_{PV}
- Hadron identification power degrades as a consequence of increased number of tracks in the event
- The challenge is to at least maintain the same performance of run1 and run2
- In order to retain the same performance the RICH was upgraded





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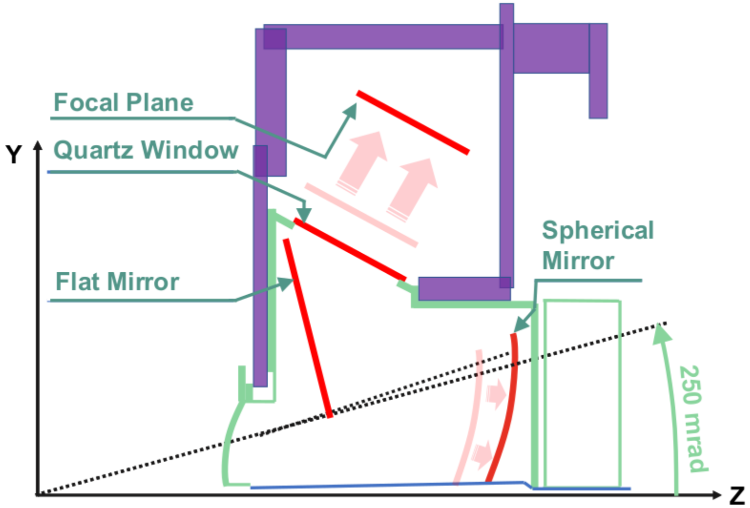
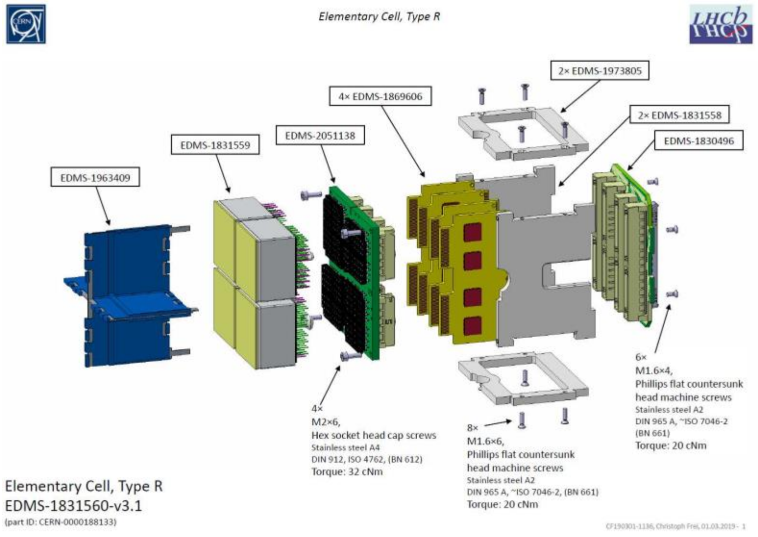
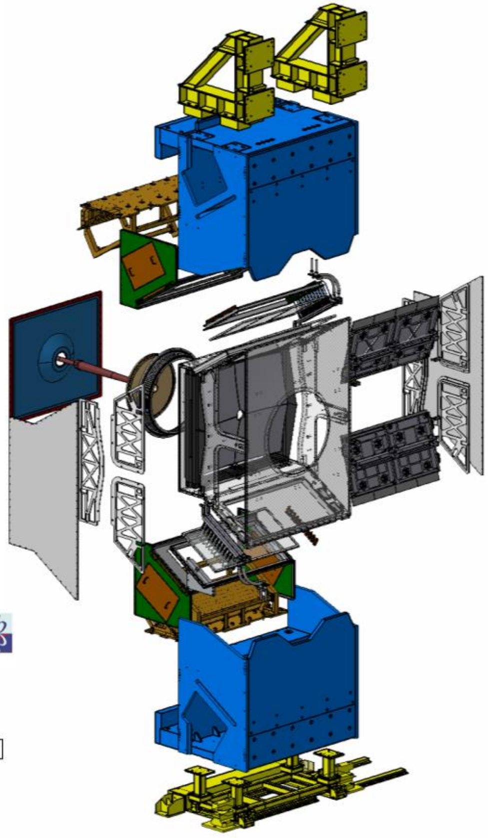
RICH Upgrade: modifications to the optics and opto-electronic chain



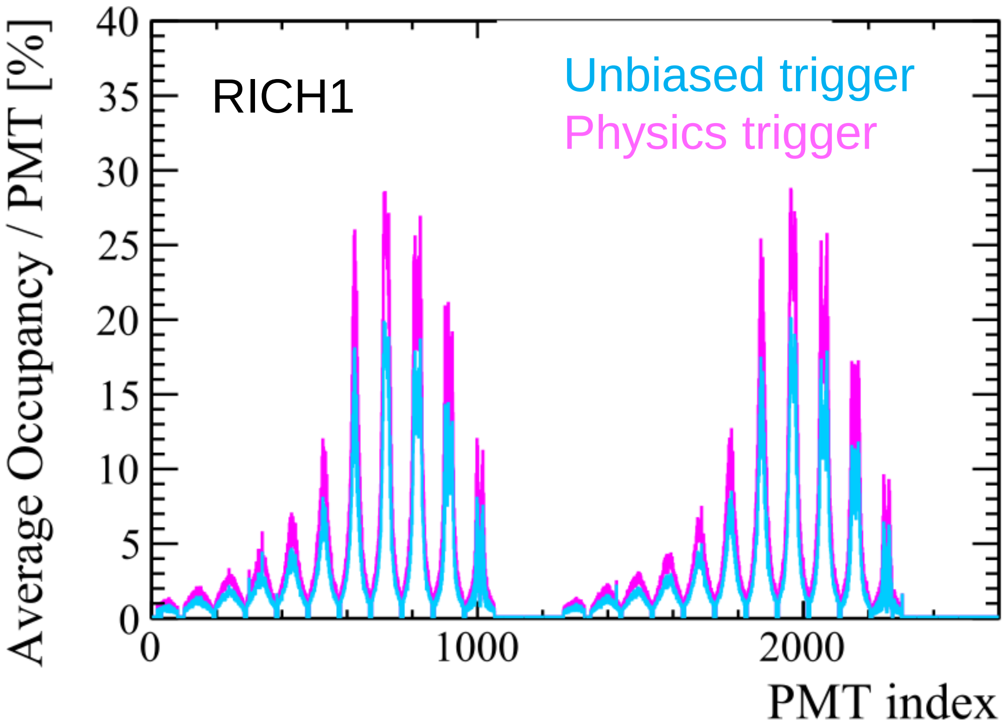


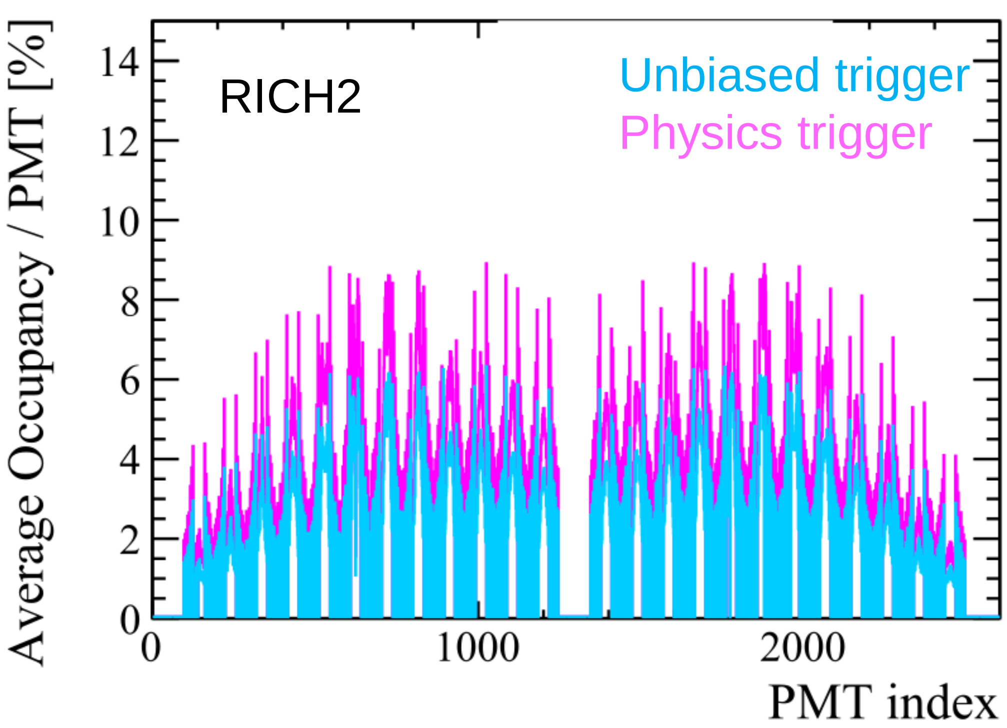


- In order to keep the peak occupancy below 30% increase the focal length of the spherical mirror by $\sqrt{2}$
- New mirrors, mechanical support
- → Cherenkov ring expands
  - Peak occupancy halved
  - Reduced Pixel granularity contribution
    $\sigma_{pix} = \frac{d_{pix}}{R} / \sqrt{3}$
  - Reduced σ_{ep}
- Opto-electronics chain
  - Replace HPD with multi-Anote Photomultiplier Tubes (MaPMTs)
  - Replace front-end with CLARO8 [M. Baszczyk et al 2017 JINST 12 P08019] and DAQ with 40Mhz FPGA-based digital board

Occupancy

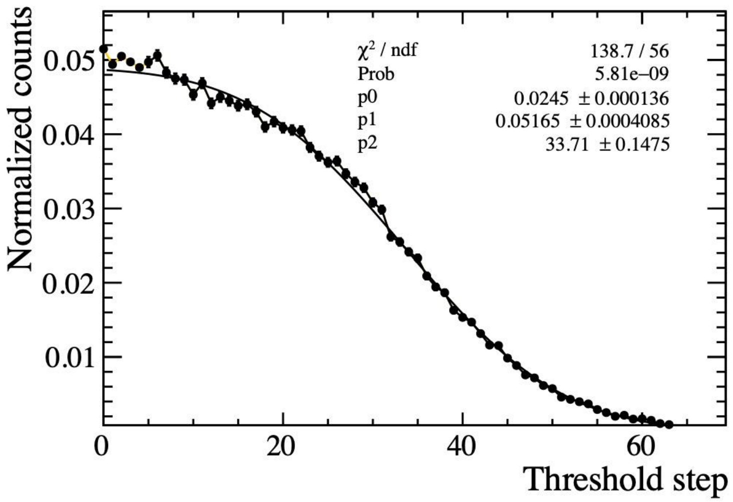
- Values below 30% are necessary to guarantee optimal performance
- Measured in real data at run3 nominal running conditions ($\mu = 5.5$, 40MHz readout)
  - With unbiased triggers: relevant for operation of PMT
  - With physics triggers: relevant for PID performance

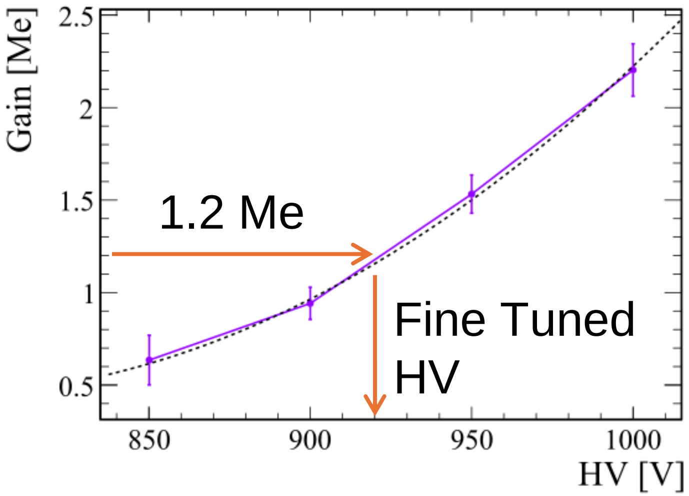


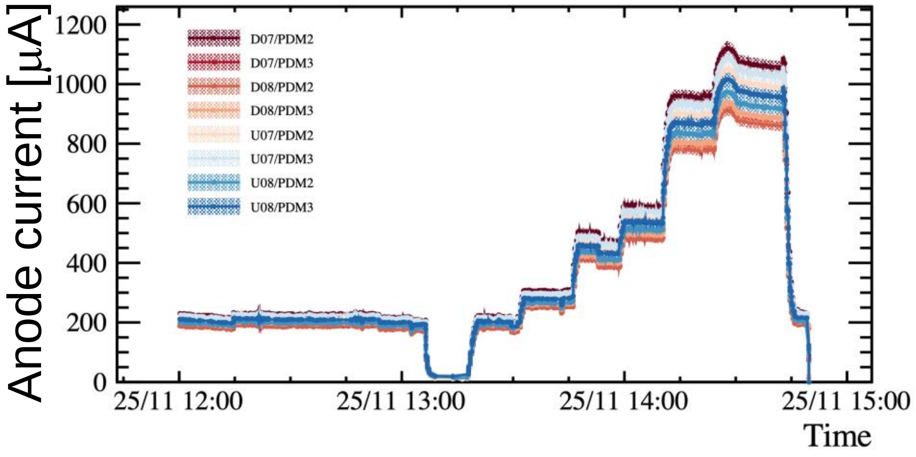


PMTs Working point optimization and operation

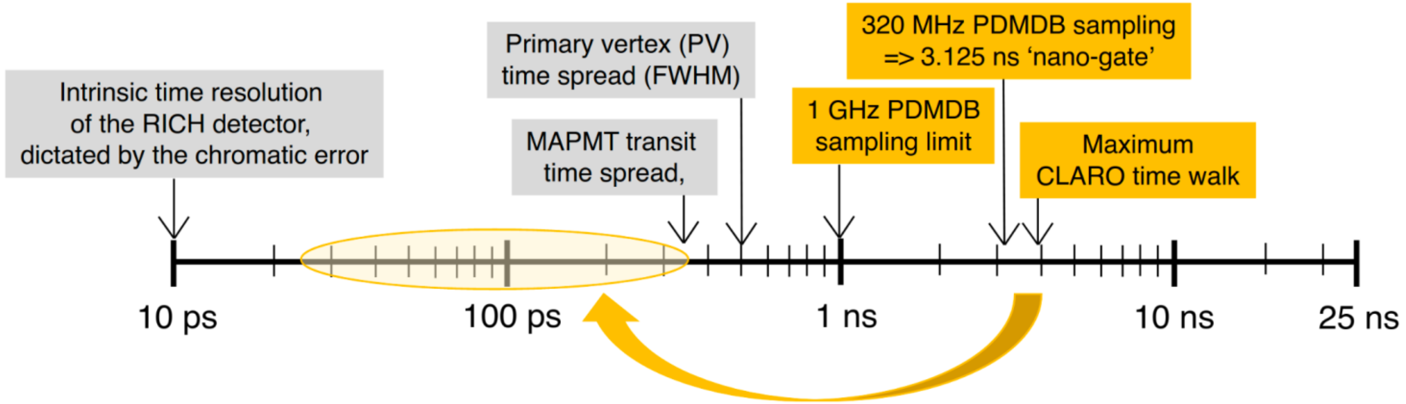
- We implemented a system to measure online the PMT gain
- Tuning of the PMT Gain important for threshold calibration, monitoring of PMT ageing
    - Measured online from CLARO threshold scans at various HV
    - Threshold set to 200ke
    - Gain equalized across the plane and set to 1.2Me
    - No ageing was observed in run3
- Luminosity
    - Last dynode powered independently → linear response up tp high rates
    - Anode currents can used to measure luminosity online



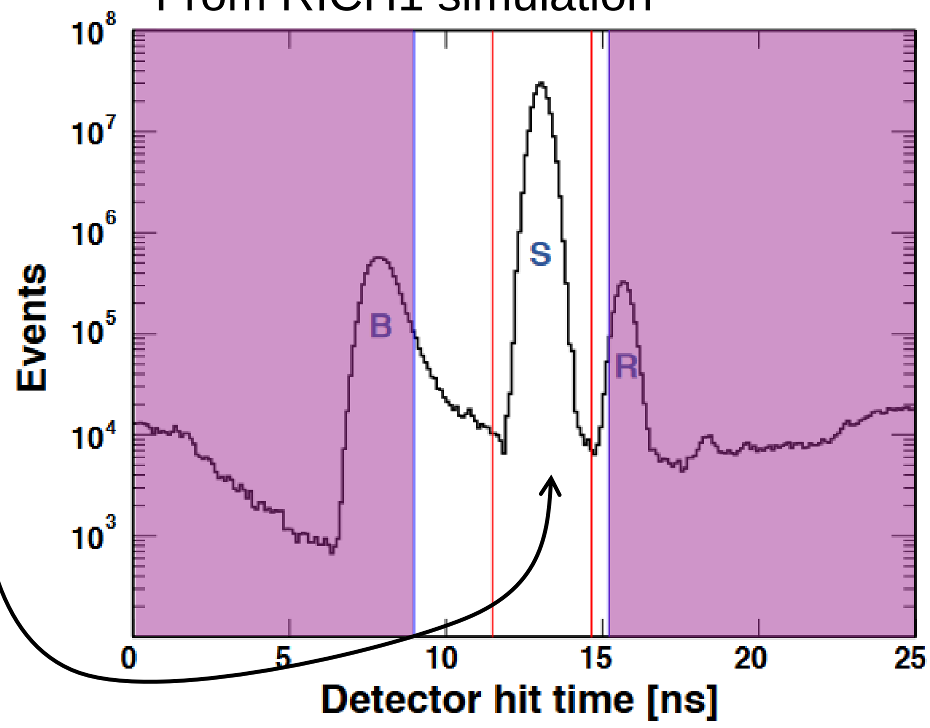




Time Gating



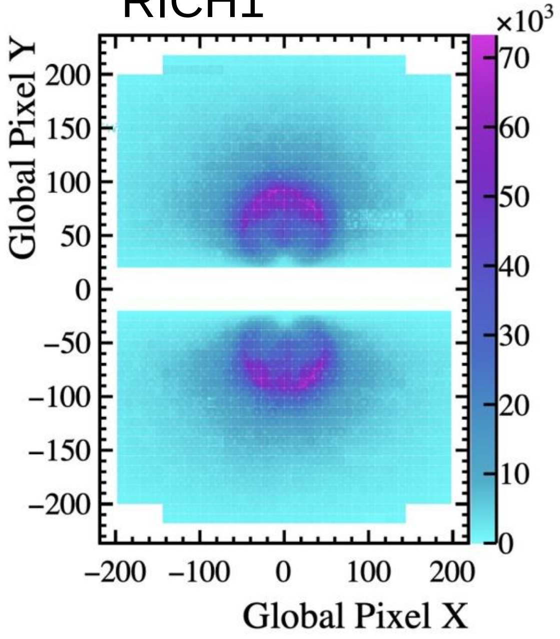
- We exploited resources on the digital board to implement time gating in order to remove background photons
- Leverage on: RICH Cherenkov photons (S) time of arrival is highly predictable
  - Track reconstruction + photon path ~ $10ps \oplus \sigma_{PV}$
  - MaPMT TTs $\oplus$ CLARO Amplitude walk~few ns
- Use gate to remove out of time background:
  - Particles inpinging directly on the photo detector plane (B)
  - Multiple reflections (R)
  - Random PMT internal noise, scintillation in the radiator



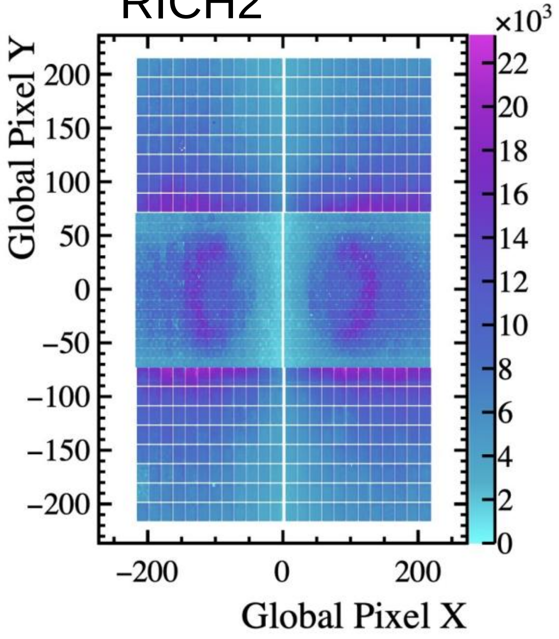
Time Alignment

- Best compromise is 6.25ns front-end hardware time gate
- The time gate has to be aligned with respect to the bunch crossing to guarantee good signal efficiency
  - Fine time alignment within 6.25 ns achieved as a routine operation
- → RICH detectors able to operate at 40 MHz, as by LHCb Upgrade design, and with further background suppression

RICH1



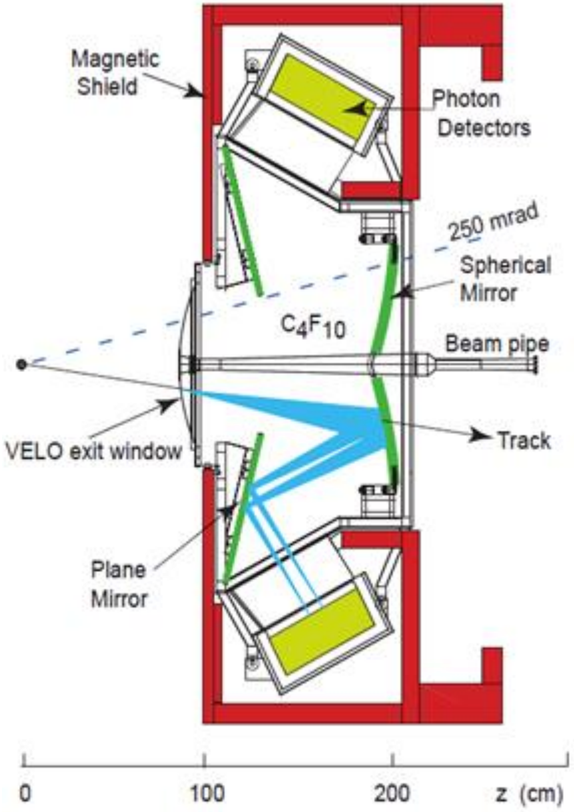
RICH2

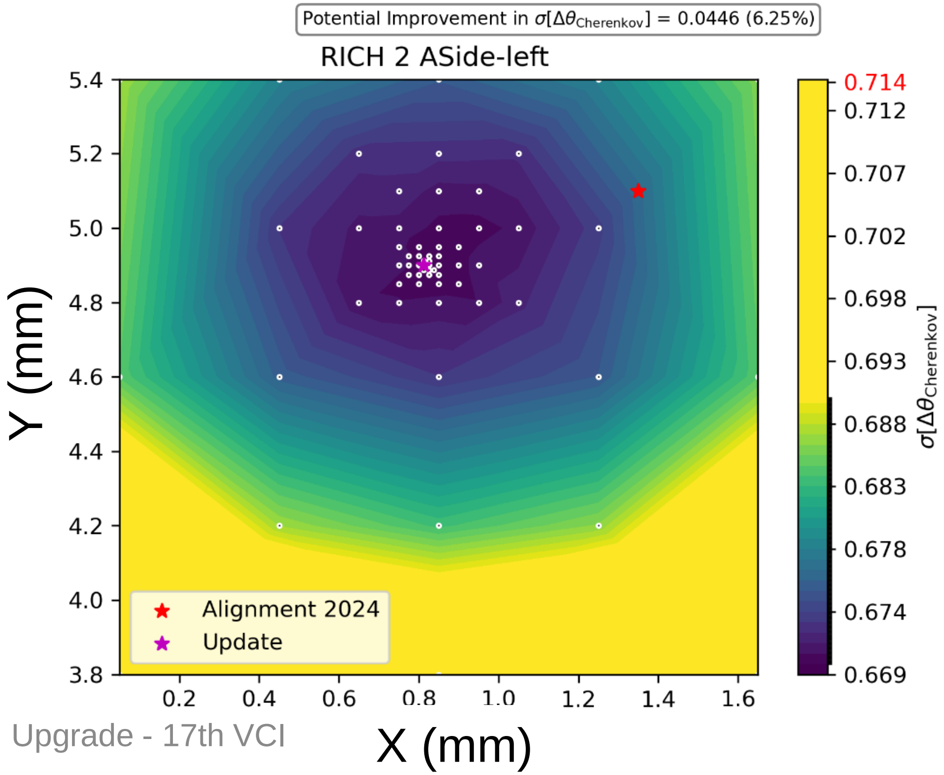


Hit map after time alignment

PMT panels Alignment

- Cherenkov angle resolution affected by the **position of the PMT** plane and the **relative alignment of the mirrors with the trackers**
- Resolution is most sensitive to the position of the PMT panels so panel alignment performed first
  - Small translations/rotations a few times per year to minimize the resolution

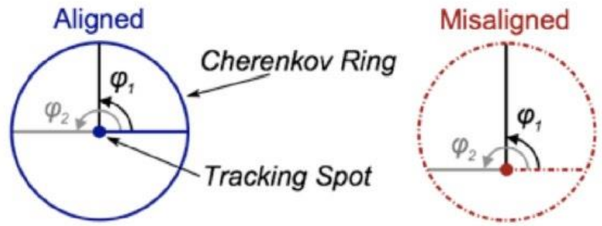


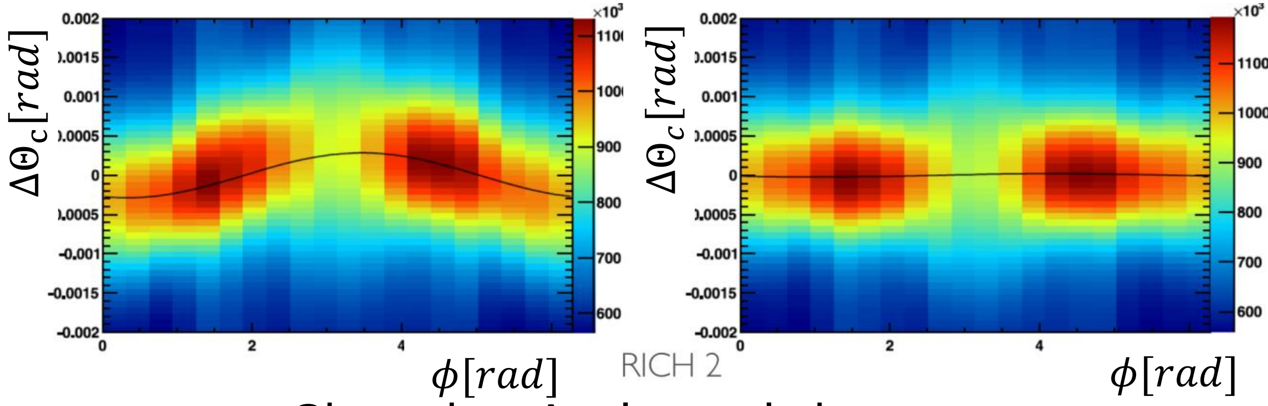


LHCb-FIGURE-2023-007
And its update

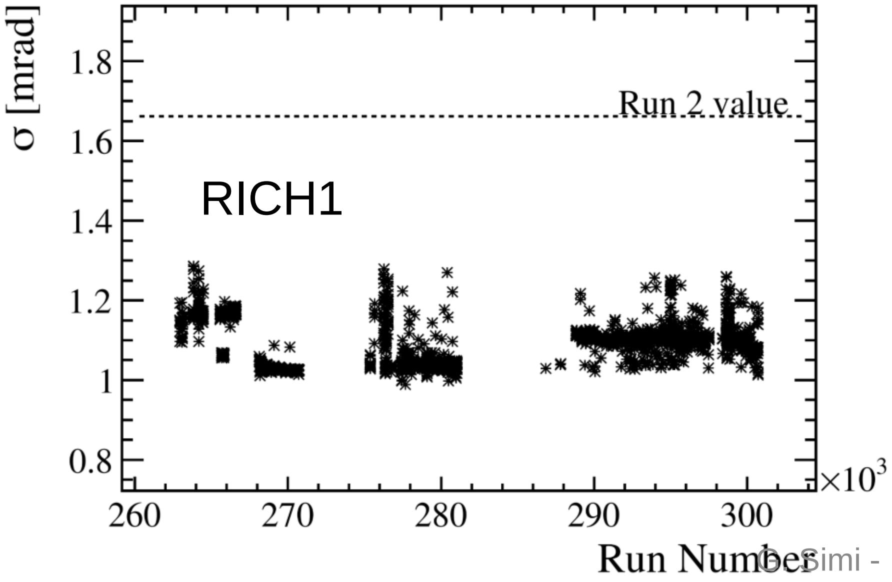
Mirrors Alignment

- Mirrors alignment performed real-time (run by run)
- Corrects for relative position of the optical system with respect to the trackers
- Resolution improved with respect to run2 and close to the expected one

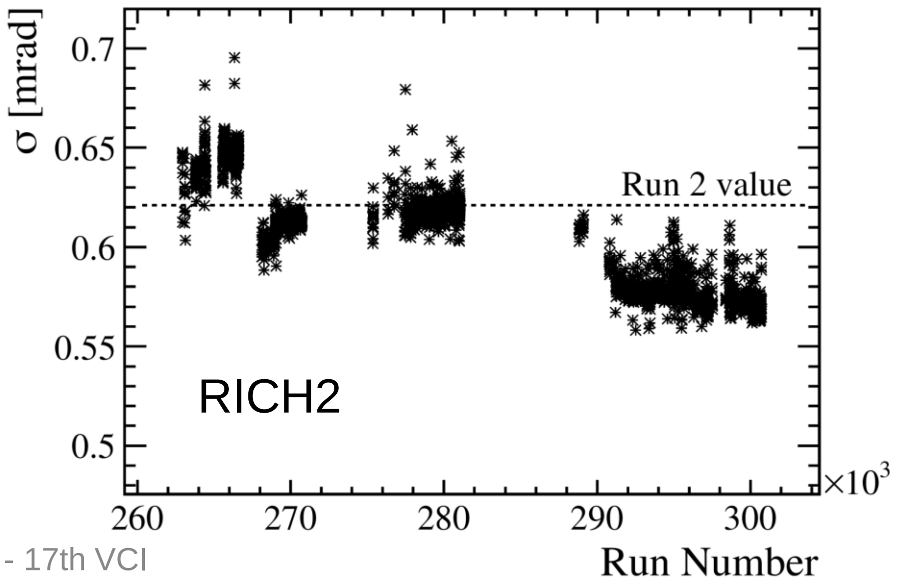




Cherenkov Angle resolution

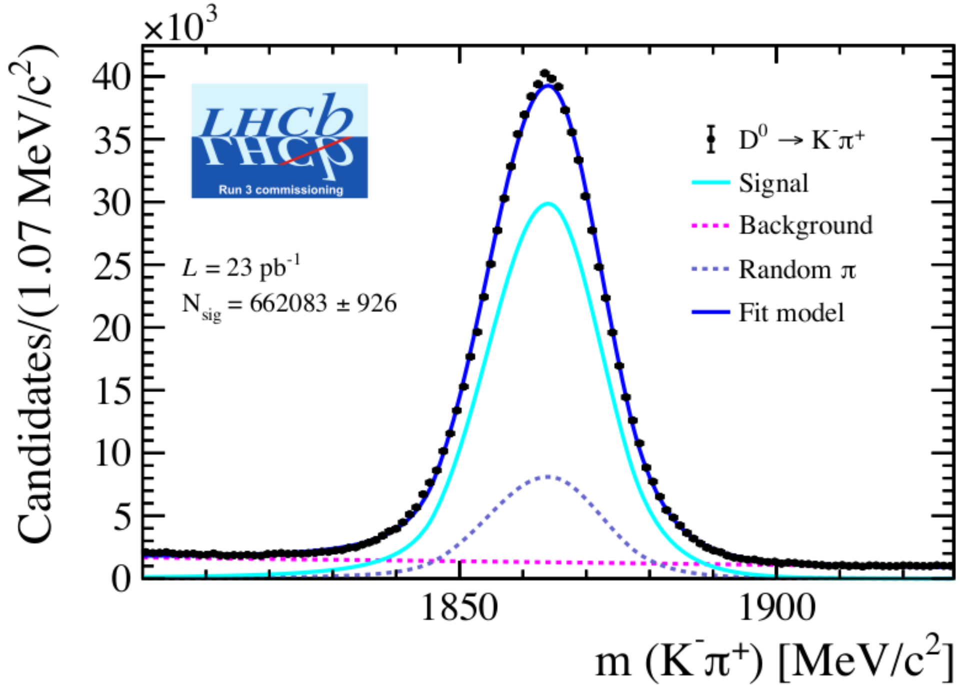


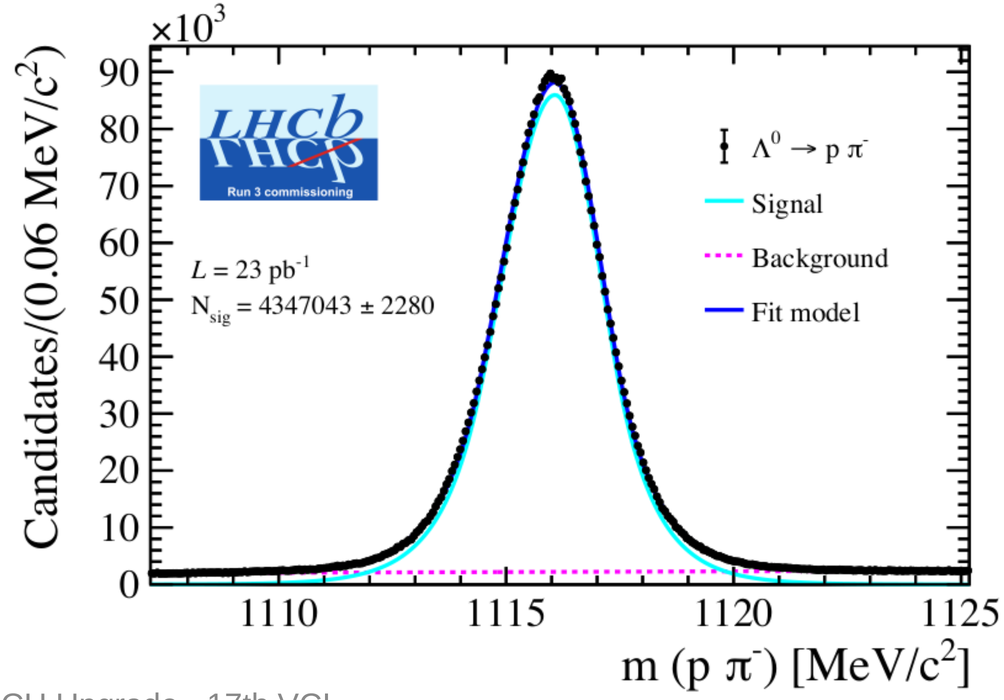
Cherenkov Angle resolution



Hadron identification

- Calibration samples are obtained from purely kinematic selection of “self tagging” modes $D^{*+} \to D^0(\boldsymbol{K^-\pi^+})\pi^+$, $\Lambda \to \boldsymbol{p}\pi^-$
- PID information for a charged track is encoded in a DLL variable
  - DLL=Log likelihood ratio $DLLh = \ln(h) / \ln(\pi)$
- Performance is determined for different selections of $DLLh$ using two methods: Fit and count and the sum of sWeights
- For both methods $\epsilon_h = \#Sig(after\ DLLh\ cut) / \#Sig(before\ DLLh\ cut)$

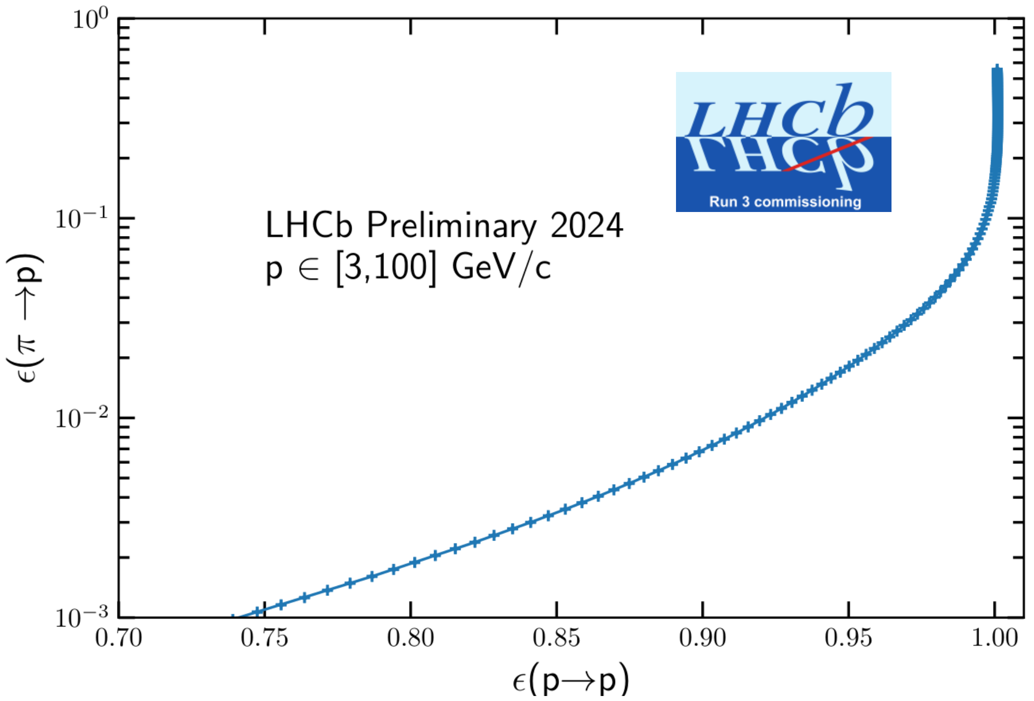




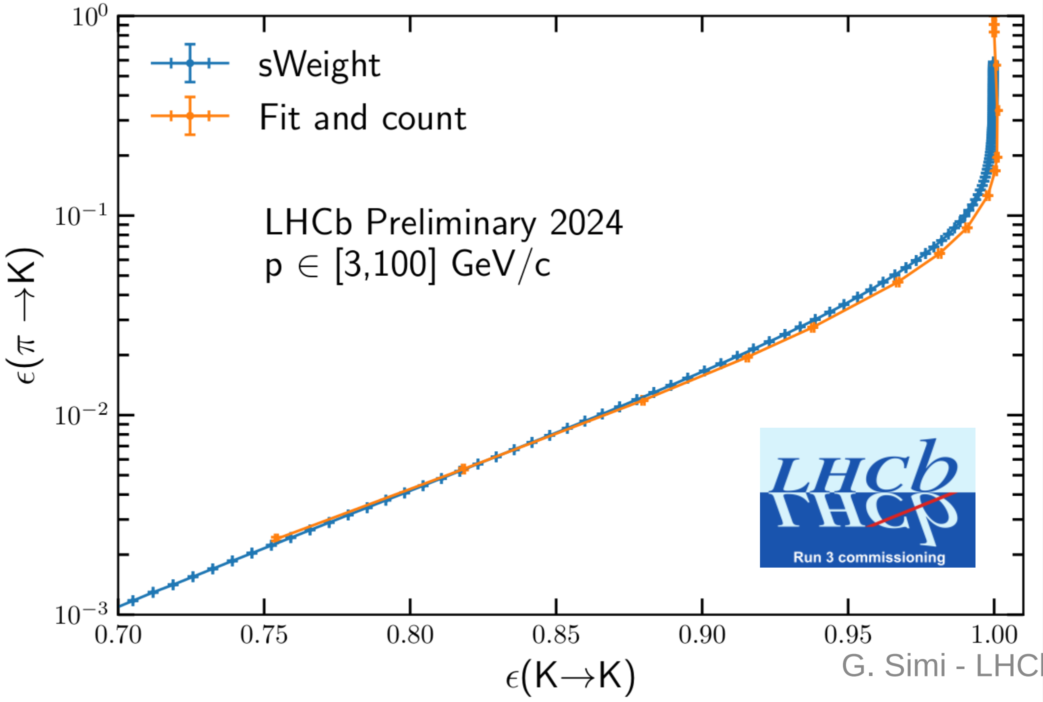
LHCb-FIGURE-2023-019

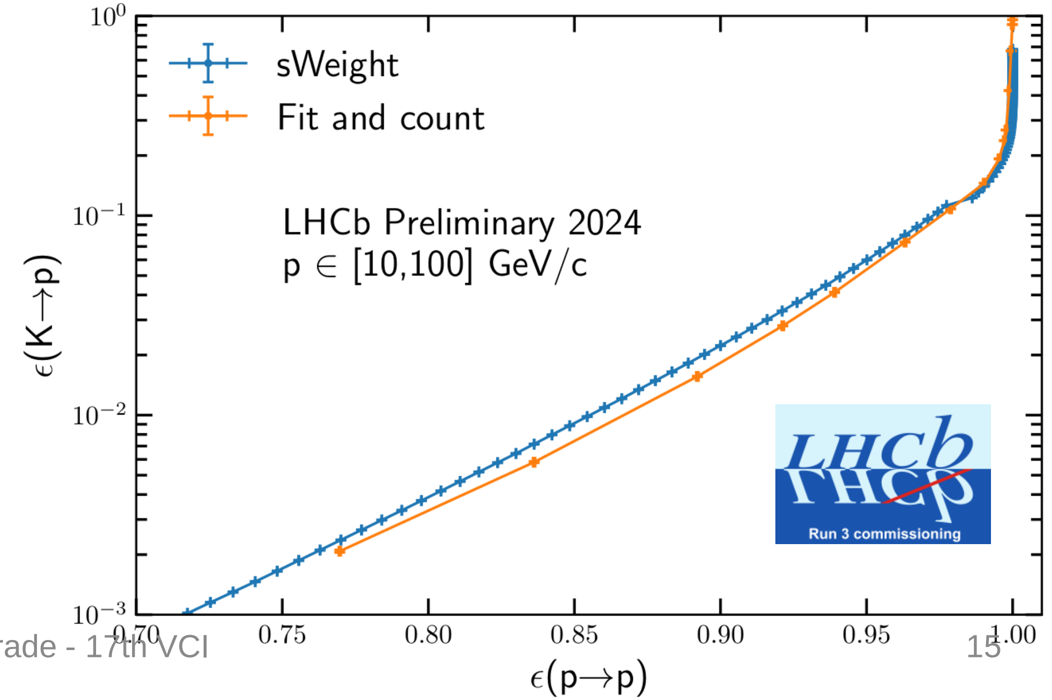
Hadron mis-id vs efficiency

- To characterize the performance we look at efficiency and mis-id probability by varying DLLh cut
- Performance improved with respect to run2



Run3 nominal conditions
NPV=4.7- 5.0, P~30-40 GeV/c2





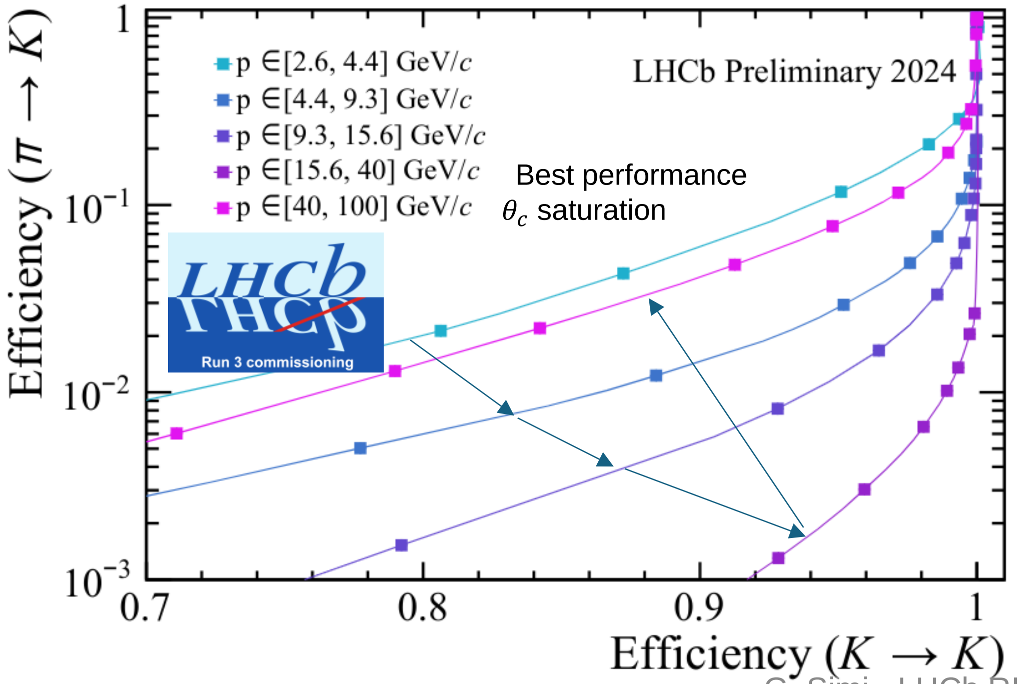
LHCb-FIGURE-2024-031

Performance vs Momentum

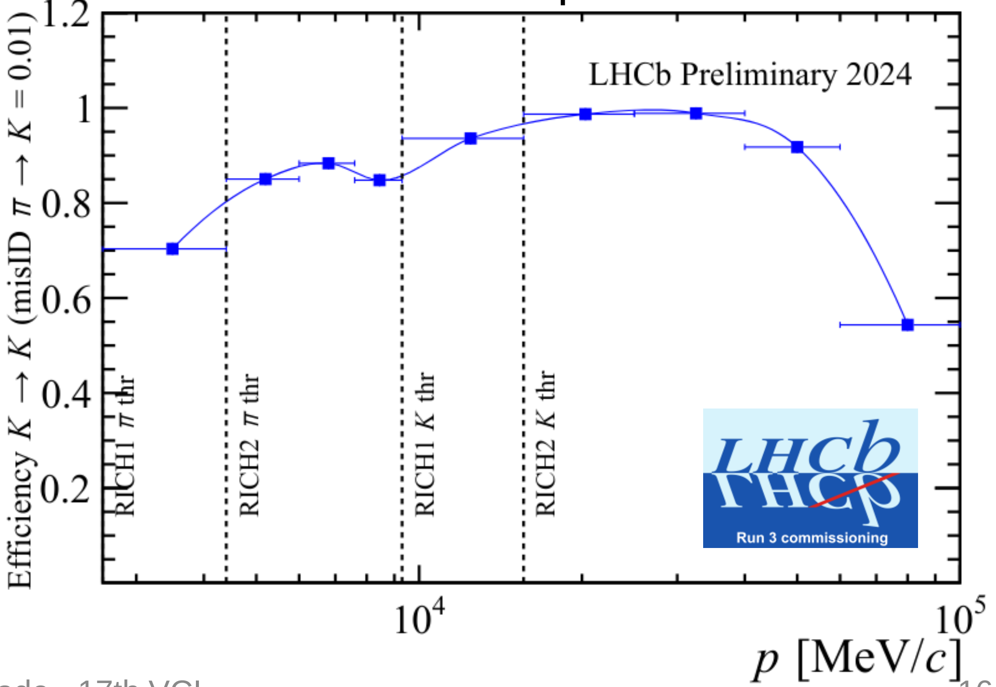
- Study the identification as a function of relevant variables to fully characterize performance
  - Identification probability depends on momentum, [pseudo-rapidity] and density of tracks

$$n_\sigma = \frac{\left|m_1^2 - m_2^2\right|}{2p^2 \Delta\Theta_c \tan(\Theta_c)}$$

Run3 nominal conditions
NPV=4.7-4.9



DLLk cut such that pion mis-id=1%

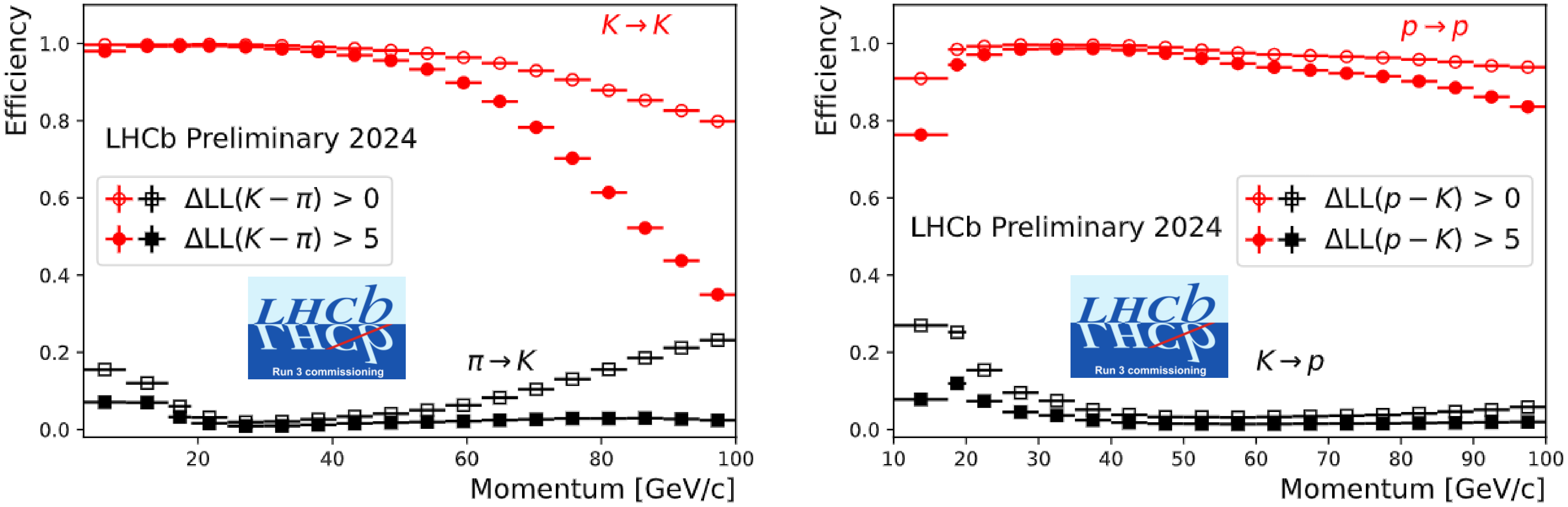


LHCb-FIGURE-2024-031

Performance vs Momentum

- Study the identification as a function of relevant variables to fully characterize performance
  - Identification probability depends on momentum, [pseudo-rapidity] and density of tracks

Run3 nominal conditions
NPV=4.9-5.0 , P=30-40 GeV/c2

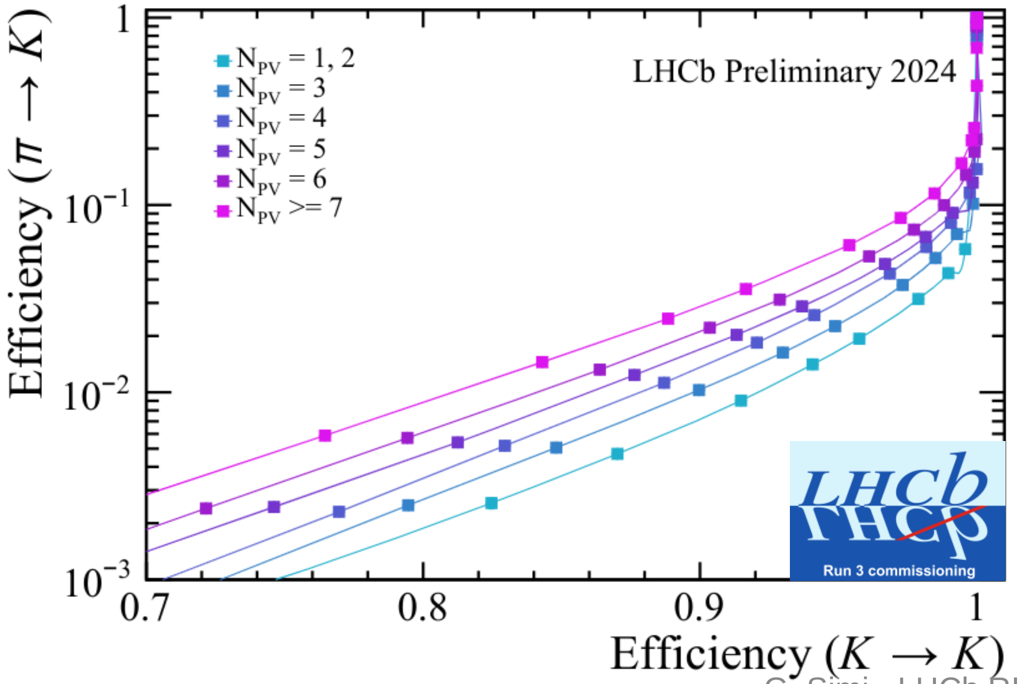


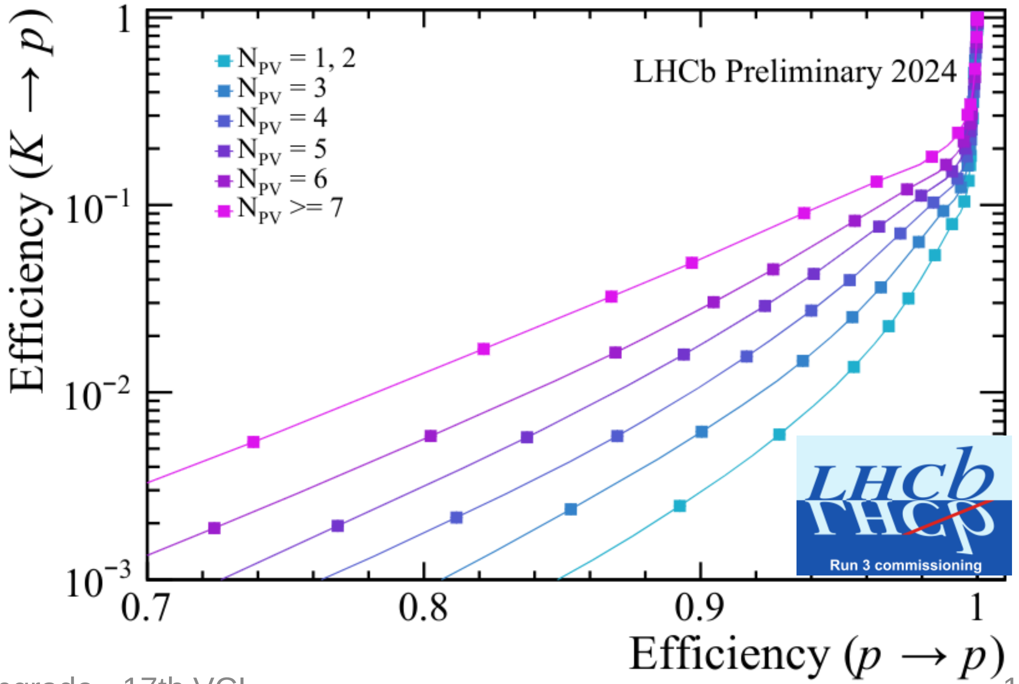
LHCb-FIGURE-2024-031

Performance vs N primary vertices

- Study the identification as a function of relevant variables to fully characterize performance
  - Identification probability depends on momentum, [pseudo-rapidity] and density of tracks

Run3 nominal conditions
P=30-40 GeV/c2





LHCb-FIGURE-2024-031

Conclusions

- LHCb RICH detector upgraded during LS2 has been running smoothly and efficiently since 2022
- Steadily approaching the design value of the Cherenkov angle resolution
- The PID performance already surpasses that of Run 2 in a more challenging environment with a 5-fold increase of the luminosity
- LHCb RICH aims to providing an excellent charged hadron discrimination power to LHCb analyses

BACKUP

RICH performance basics

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- Intrinsic contributions to σ_c
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- Contribution from tracking σ_{trk}
  - Track angle and momentum
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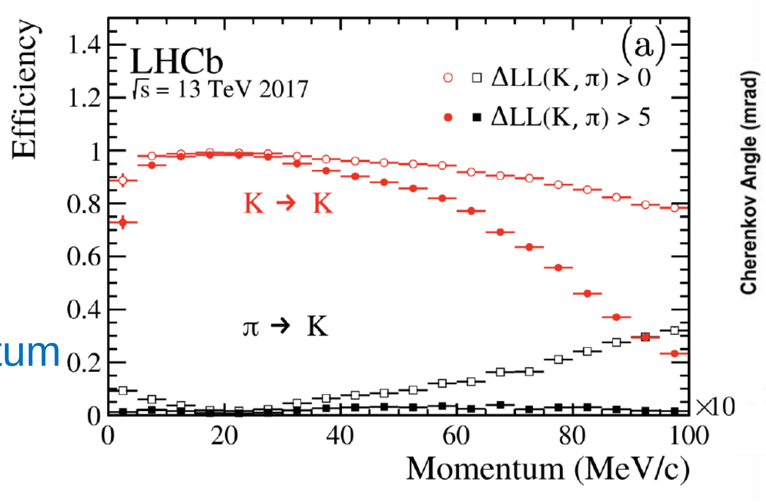
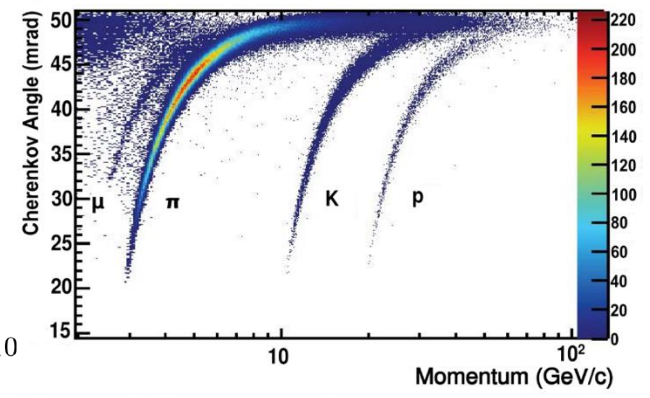
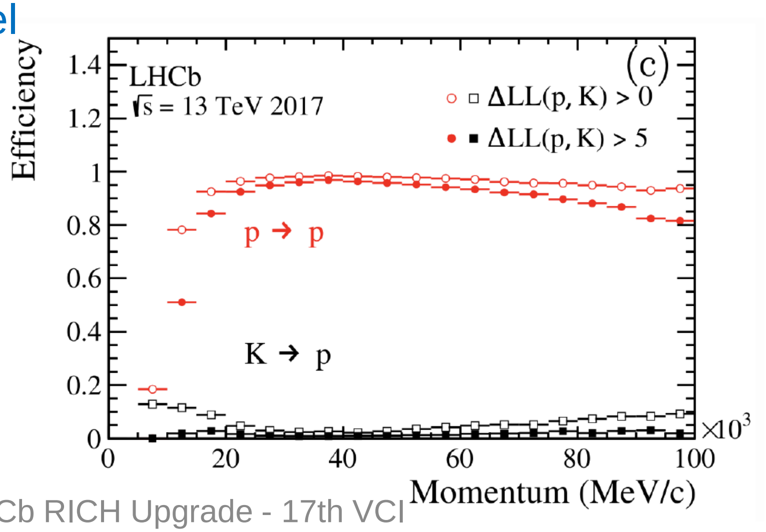
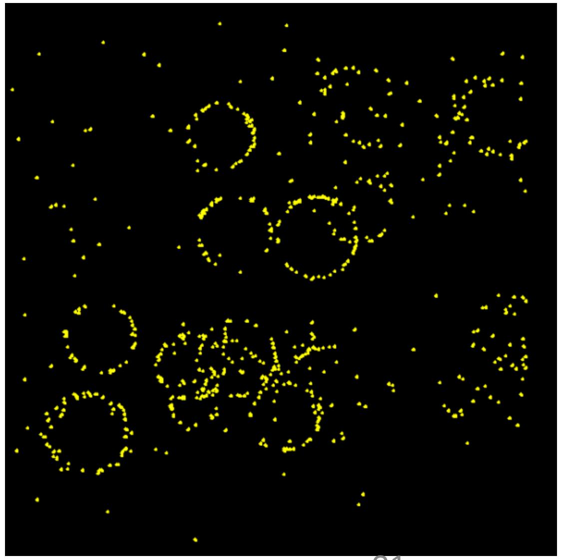


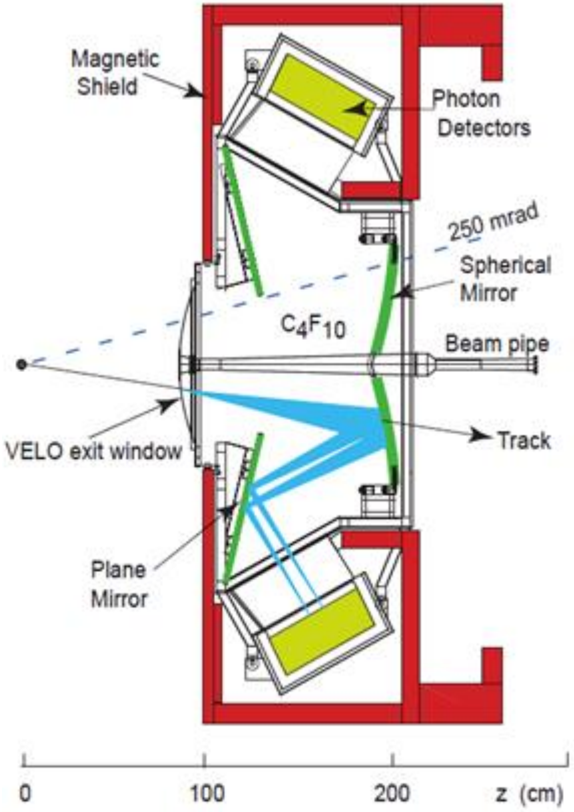


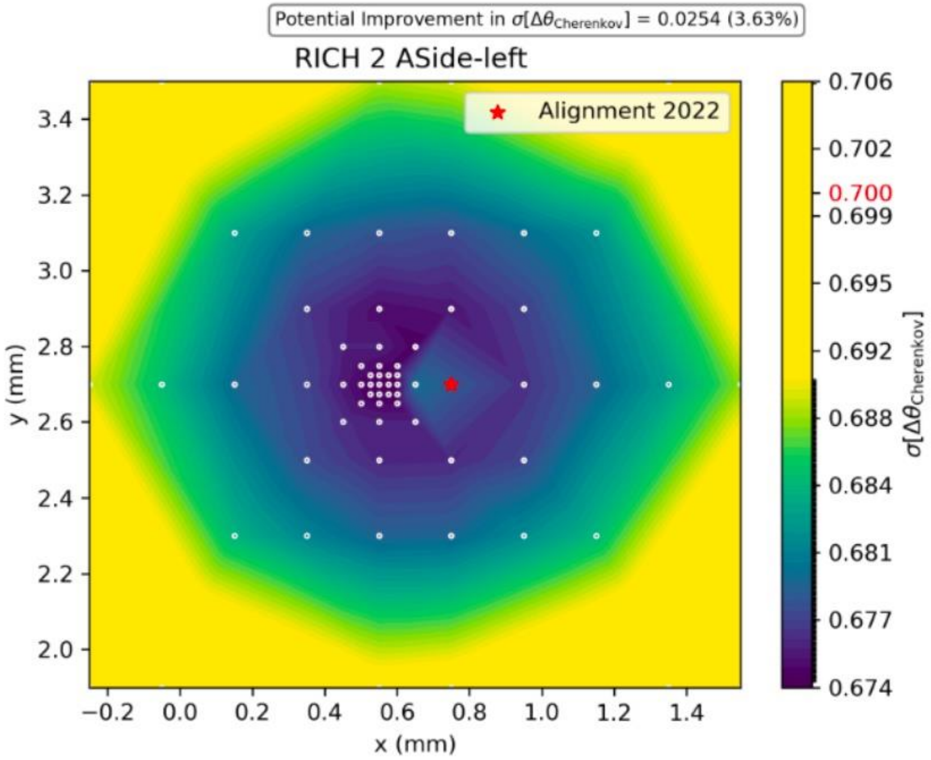




Alignment: PMT panels

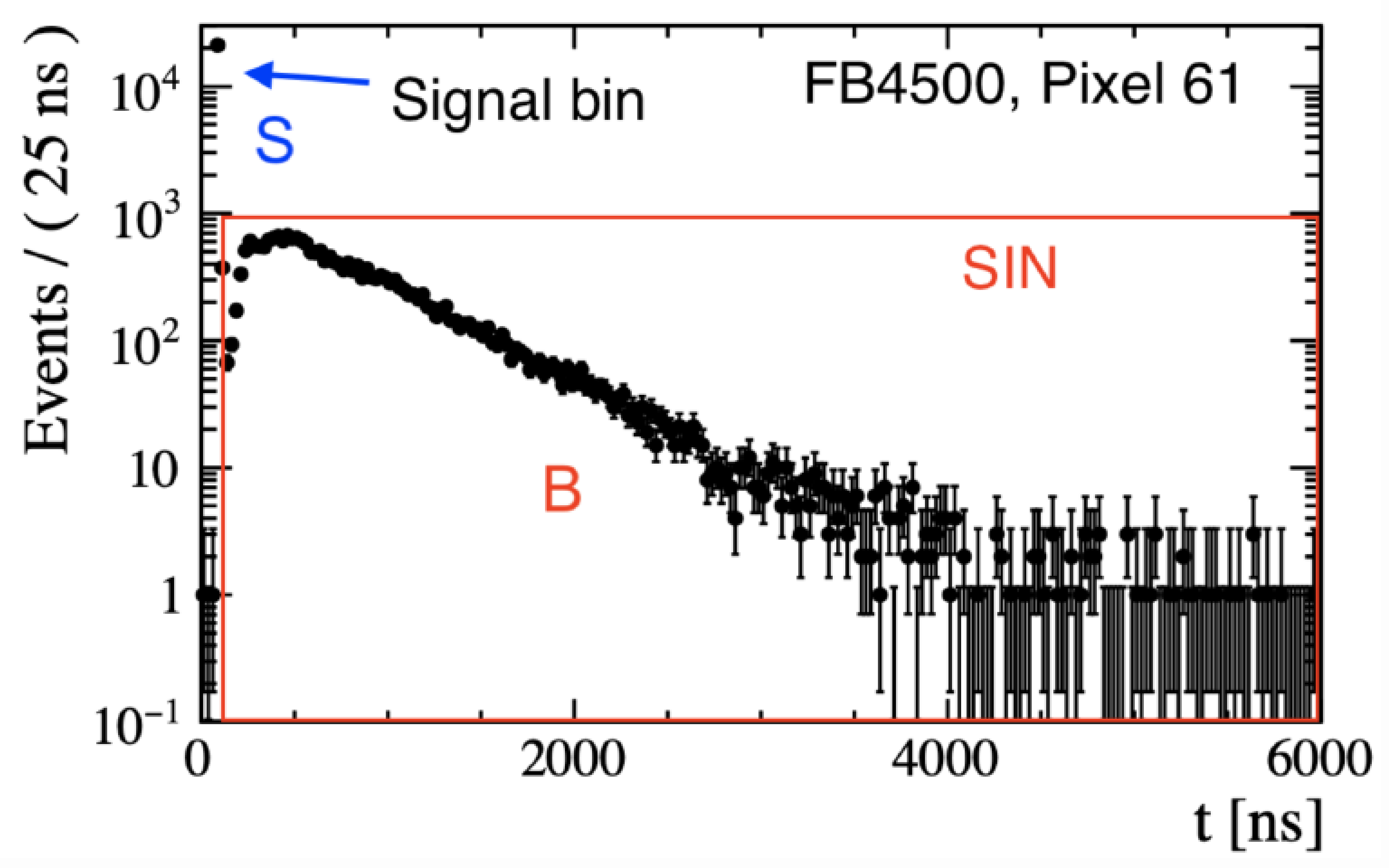
- Cherenkov angle resolution affected by the **position of the PMT** plane and the **relative alignment of the mirrors with the trackers**
- Constants defining the position of the PMT panels are the most sensitive to the resolution
- Small variations to minimize the resolution



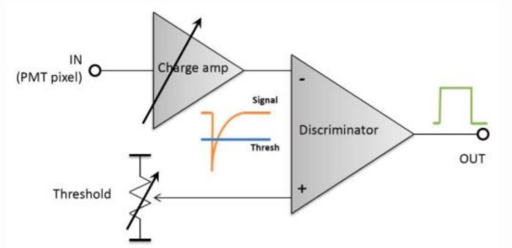


LHCb-FIGURE-2023-007

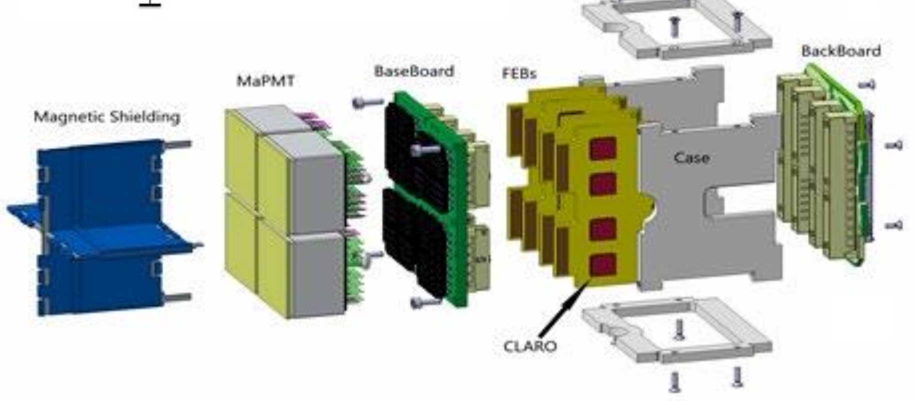
SIN

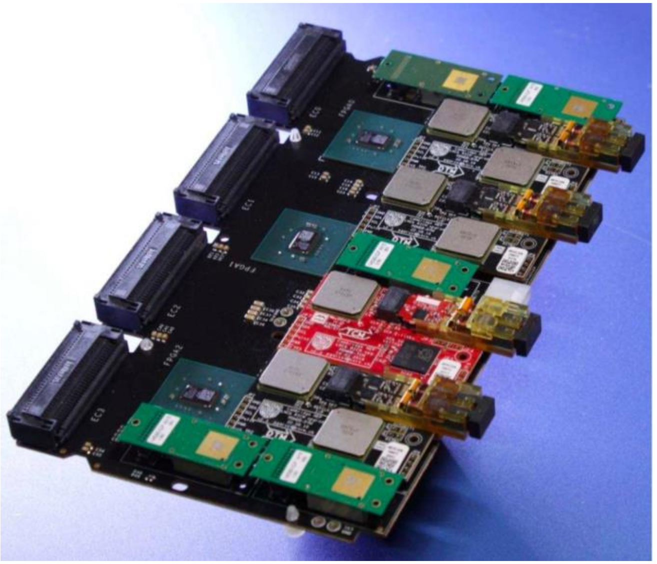


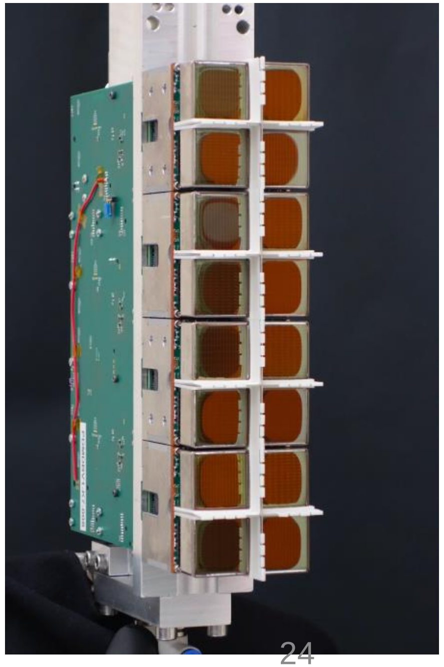
Photon detection chain



- Replace HPDs with commercial 64 channels Multi-anode photomultipliers Tubes (MaPMTs) and brand new frontend electronics
  - Magnetic shielding (RICH1)
  - MaPMTs: 2.8 x 2.8 mm2 pixel size, 80% active area, large (40% at 300 nm) quantum efficiency, G >1Me, DCR < 2.5 kHz/cm2
  - Baseboard (voltage divider and collect analog output)
  - CLARO ASIC to digitise the signal
- Flexible FPGA-based digital Board interfacing with LHCb backend boards using the GigaBit Transceiver protocol







Upgraded Photodetector planes

- Cover a large area of approximately 4 m2 with detection rates up to $\mathcal{O}$(100 MHz/cm2) in the high occupancy region down to $\mathcal{O}$(5 MHz/cm2) in the peripheral region
  - trade-off between performance and costs achieved by employing coarser granularity MaPMTs (6 x 6 mm% pixel size) in the outer region of RICH2